US009465191B2

(12) **United States Patent**
Guenter et al.

(10) **Patent No.: US 9,465,191 B2**
(45) **Date of Patent: Oct. 11, 2016**

(54) **LENSES FOR CURVED SENSOR SYSTEMS**

(71) Applicant: **Microsoft Corporation**, Redmond, WA (US)

(72) Inventors: **Brian K. Guenter**, Redmond, WA (US); **Neil Emerton**, Redmond, WA (US)

(73) Assignee: **Microsoft Technology Licensing, LLC**, Redmond, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 349 days.

(21) Appl. No.: **13/924,423**

(22) Filed: **Jun. 21, 2013**

(65) **Prior Publication Data**

US 2014/0376113 A1 Dec. 25, 2014

(51) **Int. Cl.**

G02B 9/00	(2006.01)
G02B 13/00	(2006.01)
G02B 13/16	(2006.01)
H04N 5/369	(2011.01)

(52) **U.S. Cl.**

CPC ***G02B 9/00*** (2013.01); ***G02B 13/003*** (2013.01); ***G02B 13/004*** (2013.01); ***G02B 13/0035*** (2013.01); ***G02B 13/16*** (2013.01); *H04N 5/3696* (2013.01)

(58) **Field of Classification Search**

USPC 359/754

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,638,500	B2 *	1/2014	Gallagher et al.	359/642
2005/0219716	A1	10/2005	Koike	
2013/0003196	A1	1/2013	Guenter et al.	
2013/0063634	A1	3/2013	Yamano	
2013/0076900	A1	3/2013	Mrozek et al.	

FOREIGN PATENT DOCUMENTS

JP 2008-249909 A 10/2008

OTHER PUBLICATIONS

"International Search Report & Written Opinion for PCT Application No. PCT/US2014/042799", Mailed Date: Oct. 16, 2014, 12 pages.

"International Preliminary Report on Patentability Issued in PCT Application No. PCT/US2014/042799", Mailed Date: Sep. 2, 2015, 9 pages.

* cited by examiner

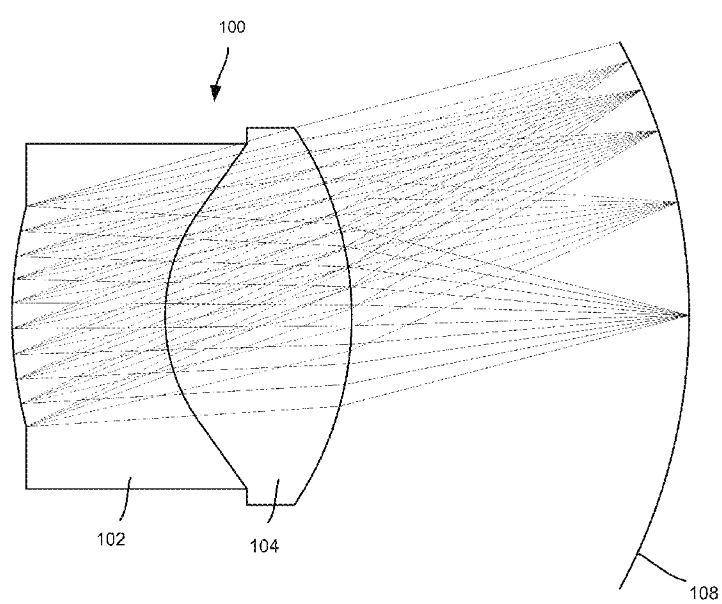
Primary Examiner — Jack Dinh

(74) *Attorney, Agent, or Firm* — Steve Wight; Sandy Swain; Micky Minhas

(57) **ABSTRACT**

The subject disclosure is directed towards lenses for curved surfaces, including multi-element lens assemblies. In one or more implementations, an object-side meniscus lens is coupled to an image/curved surface side subassembly including a biconvex lens. The subassembly may comprise a single biconvex lens or a biconvex lens coupled to a negative meniscus lens.

20 Claims, 14 Drawing Sheets



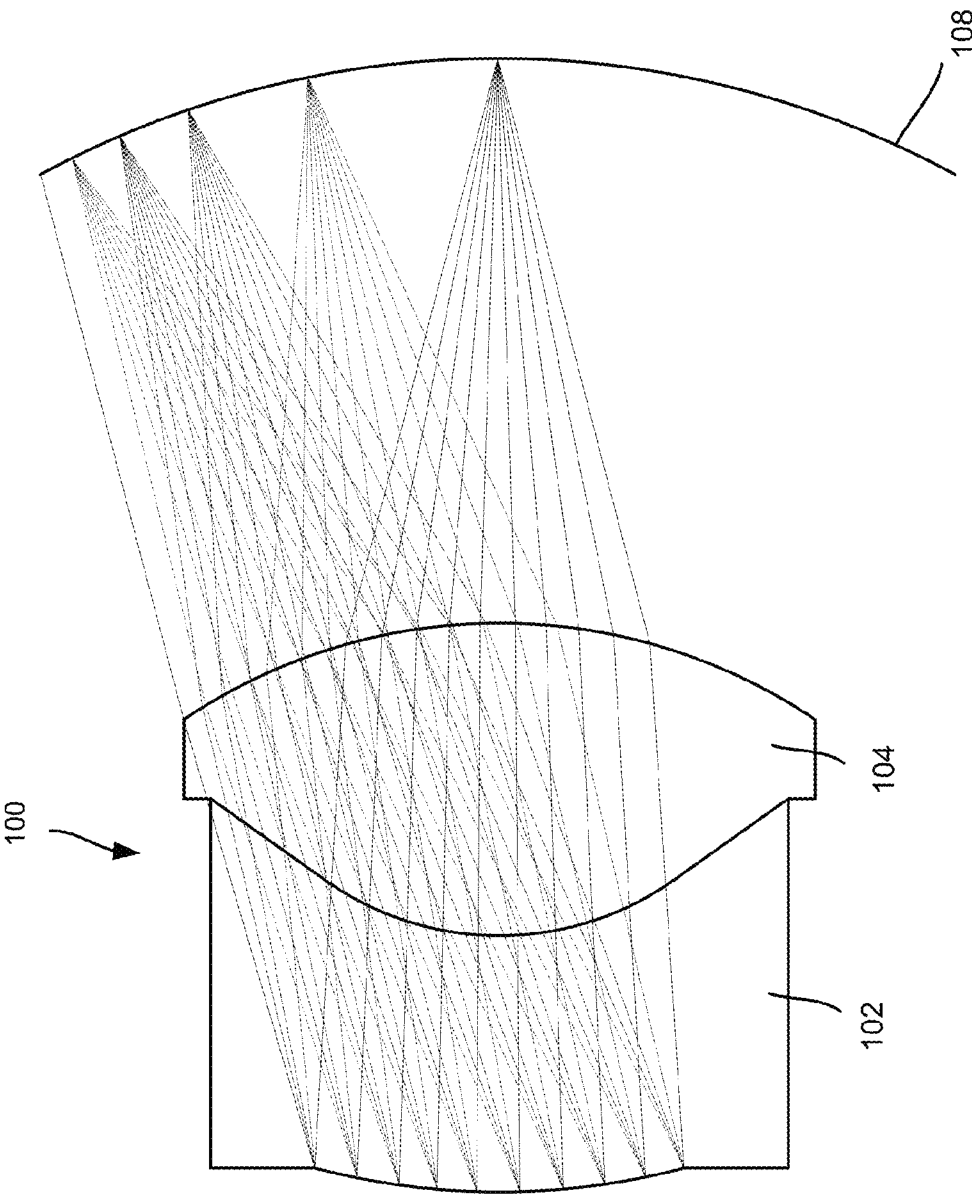


FIG. 1

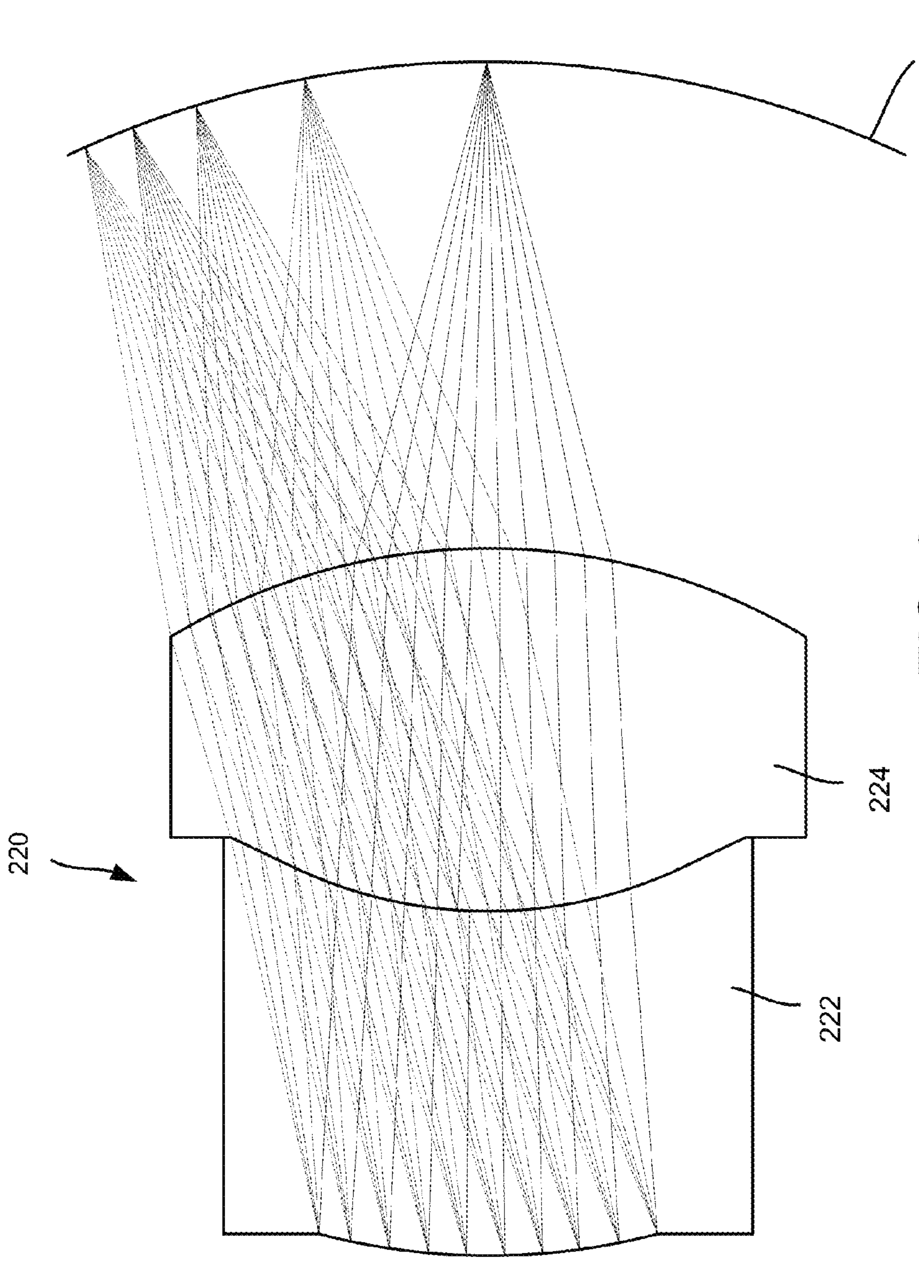


FIG. 2

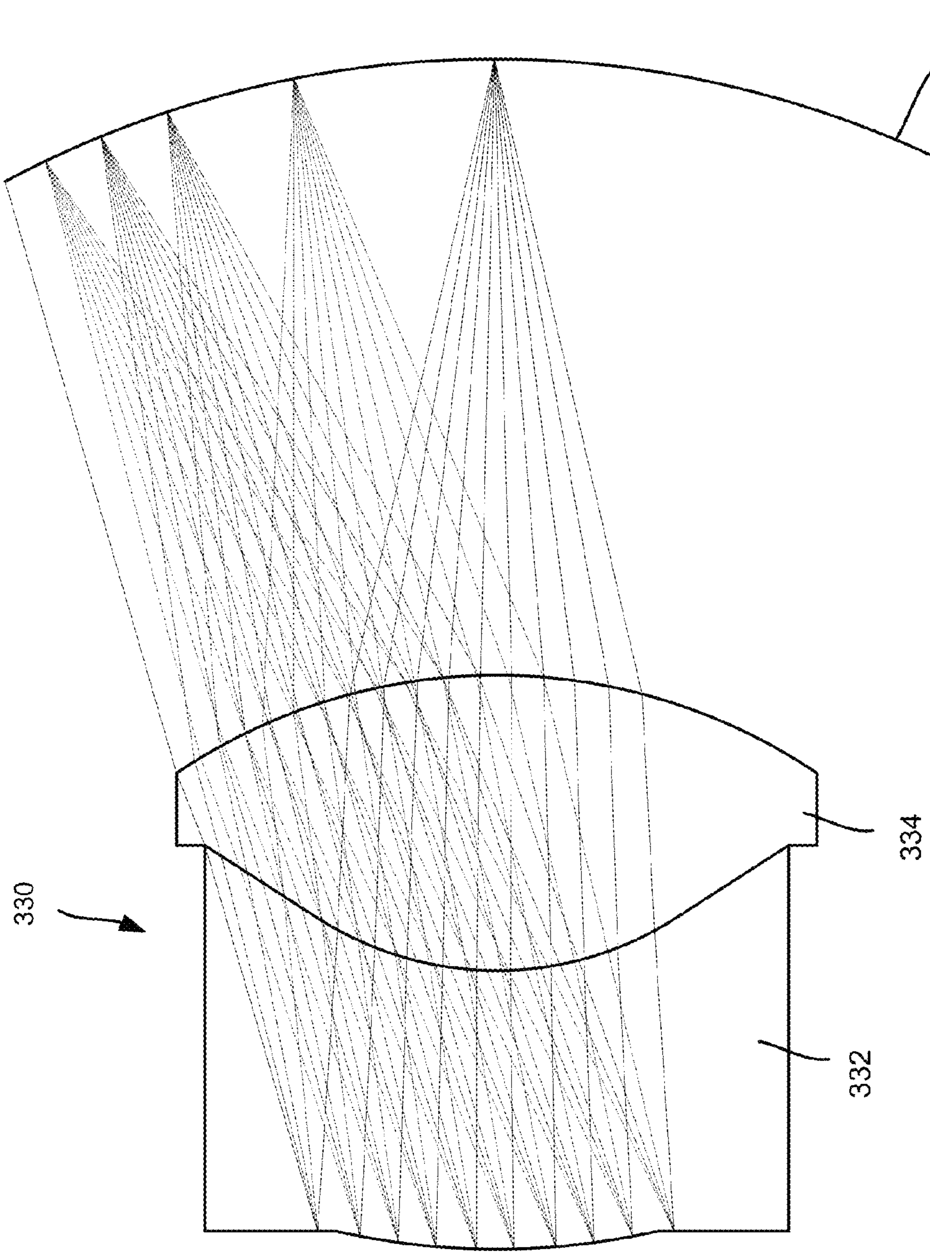


FIG. 3

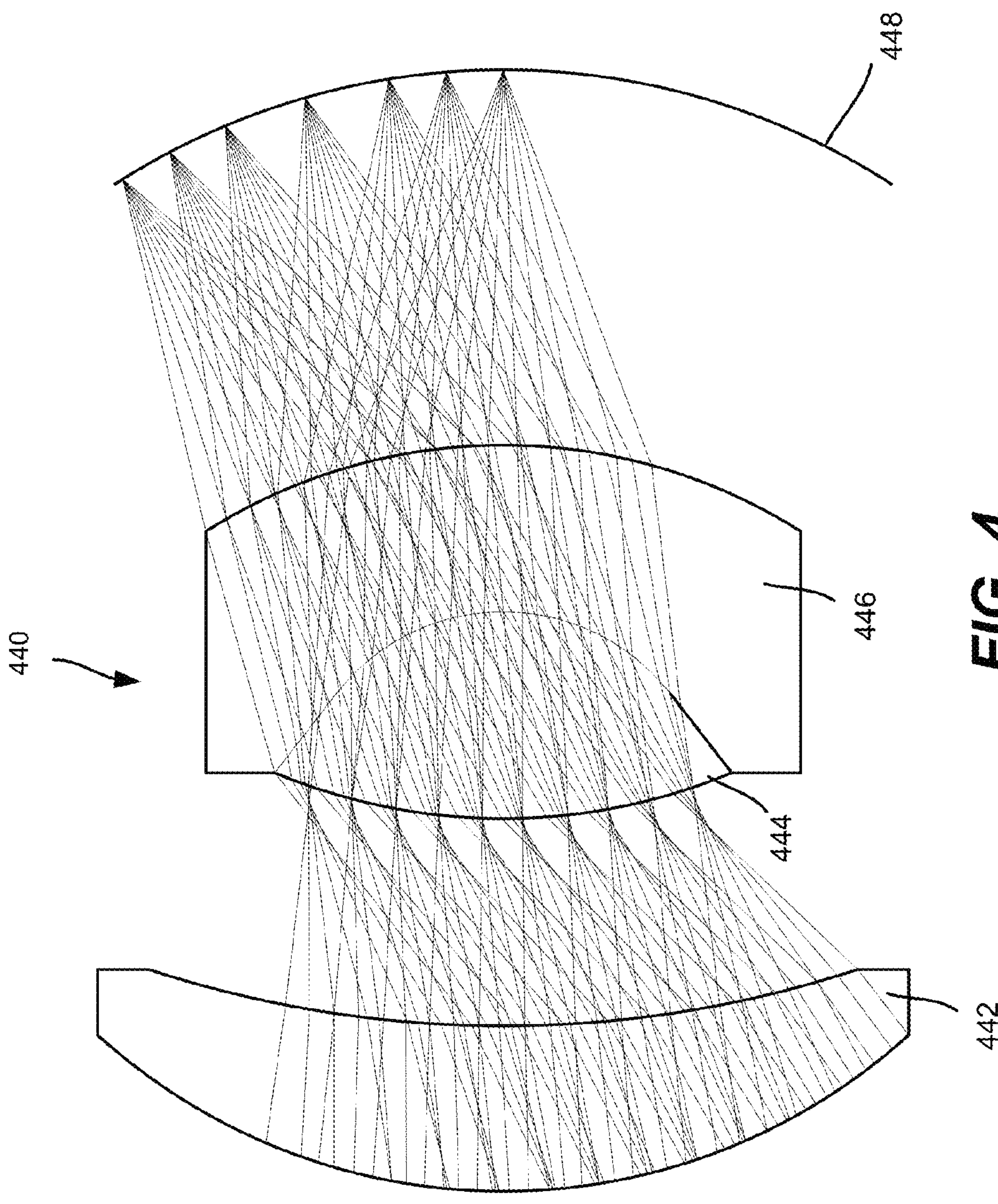


FIG. 4

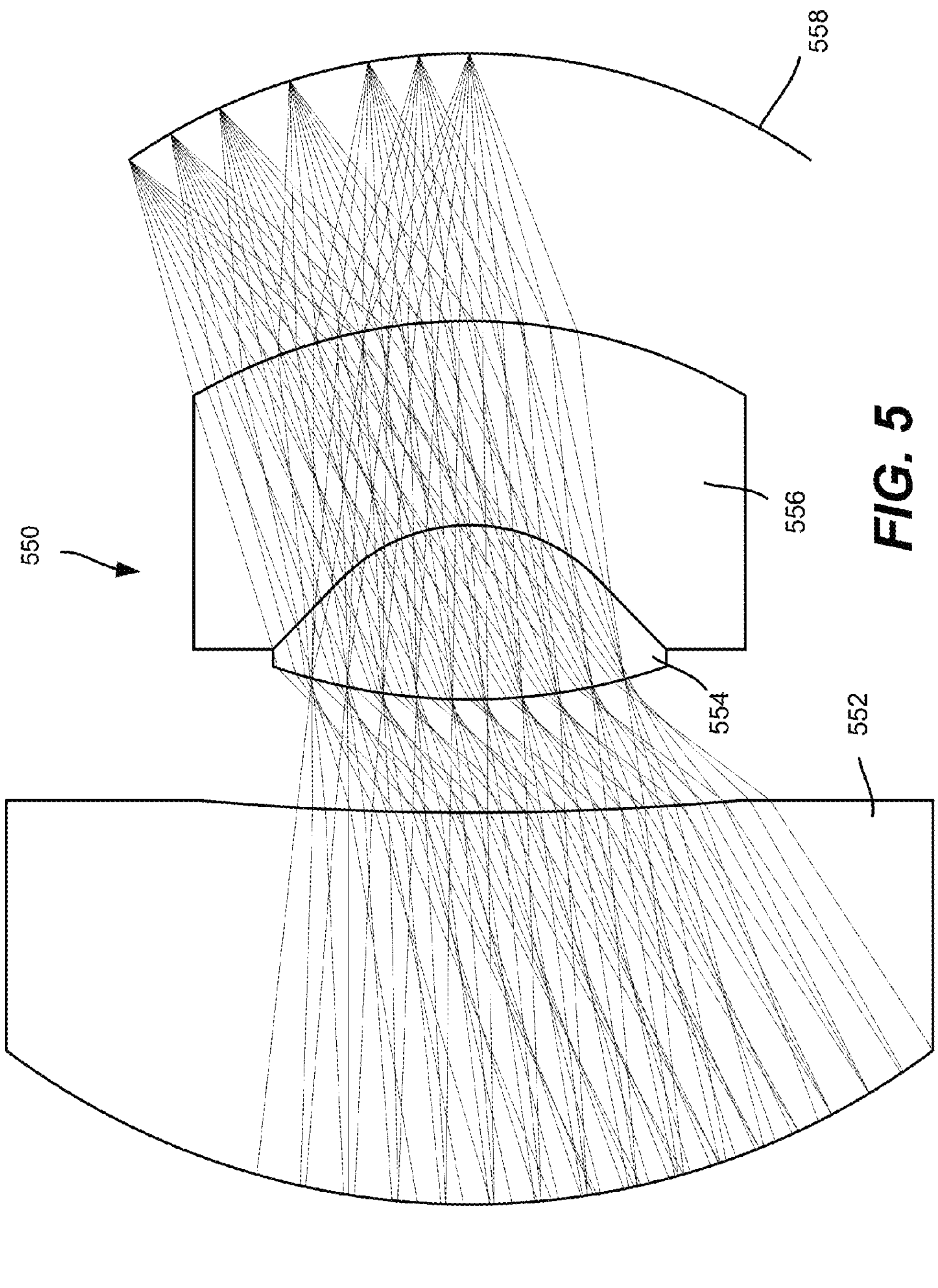


FIG. 5

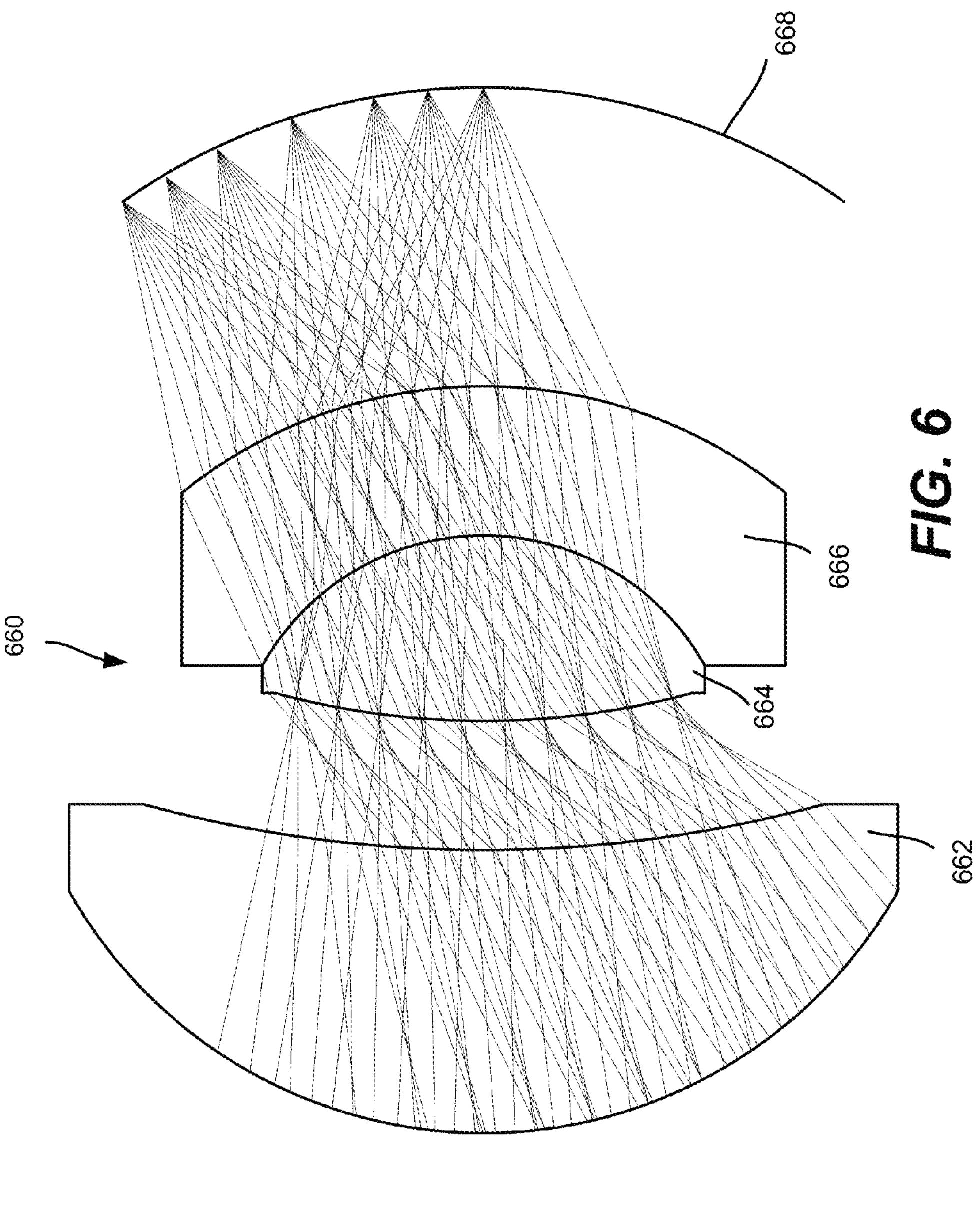


FIG. 6

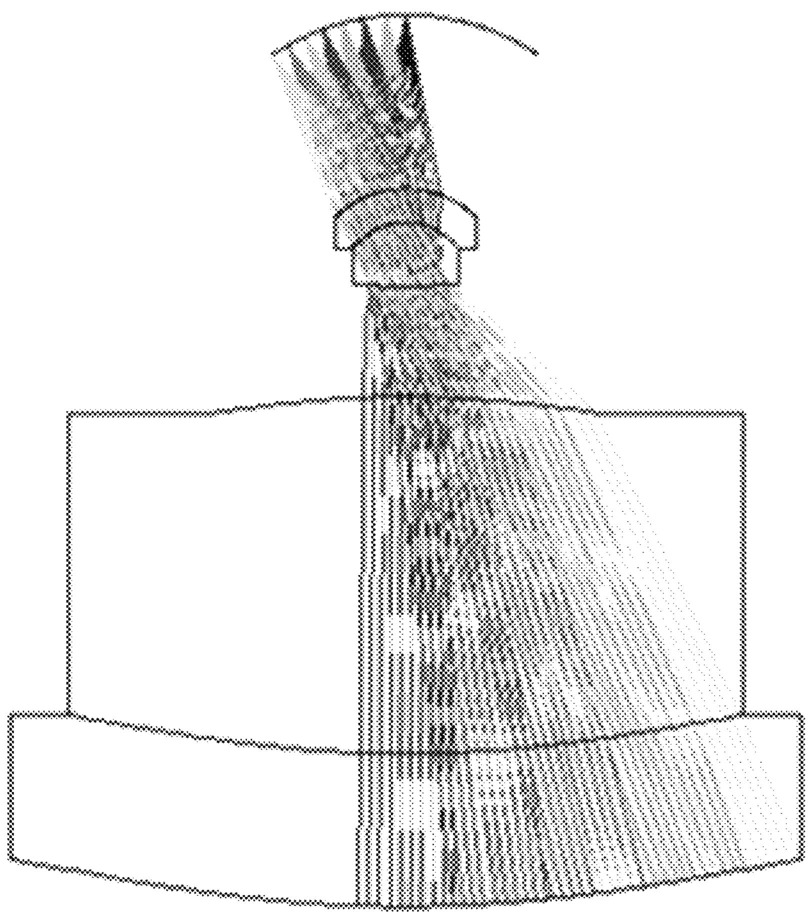


FIG. 7

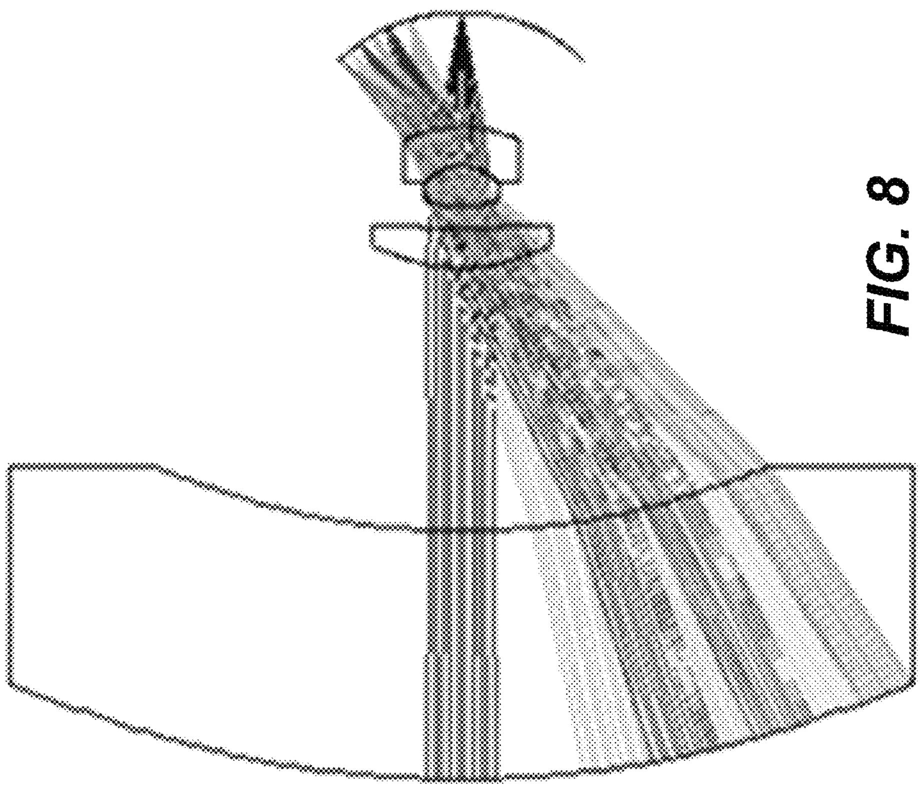


FIG. 8

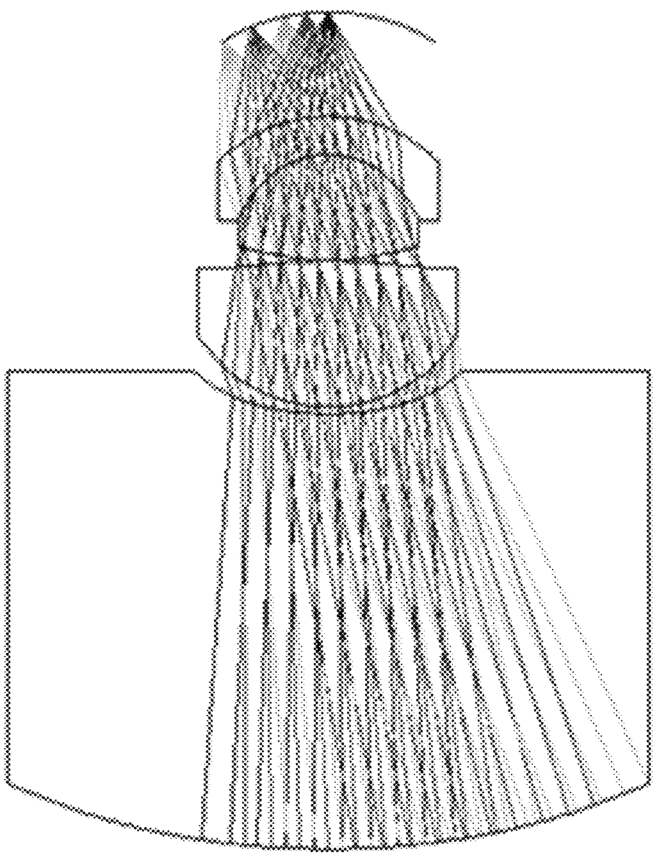


FIG. 9

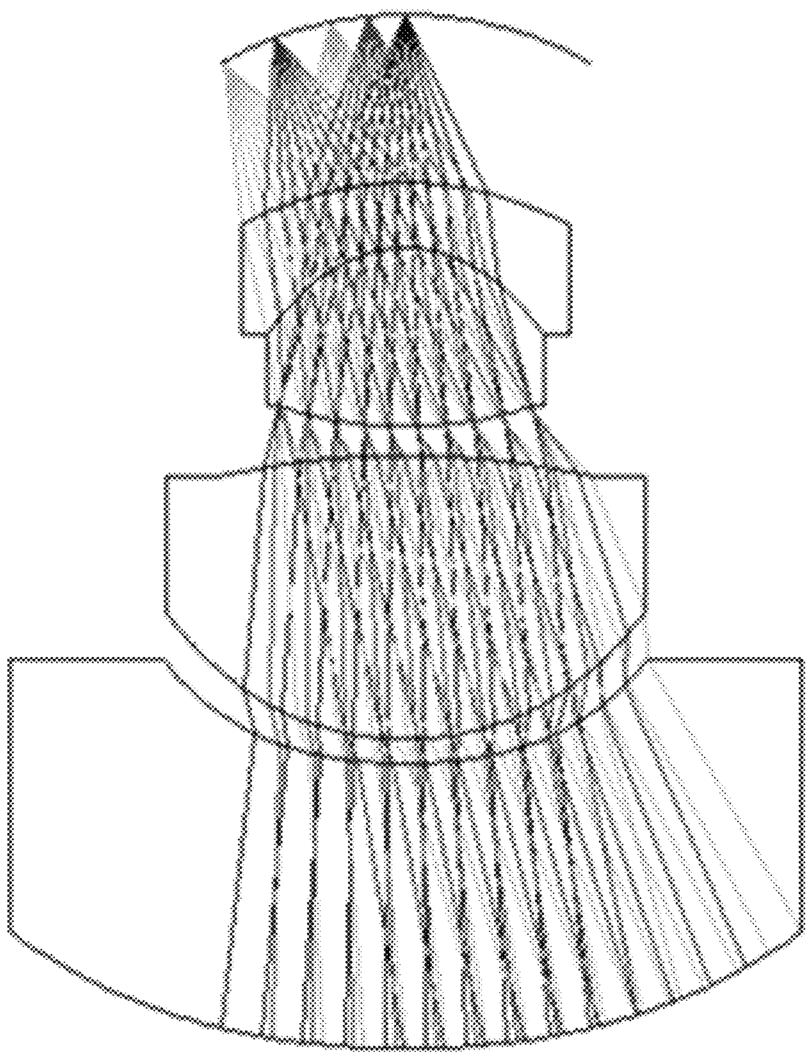


FIG. 10

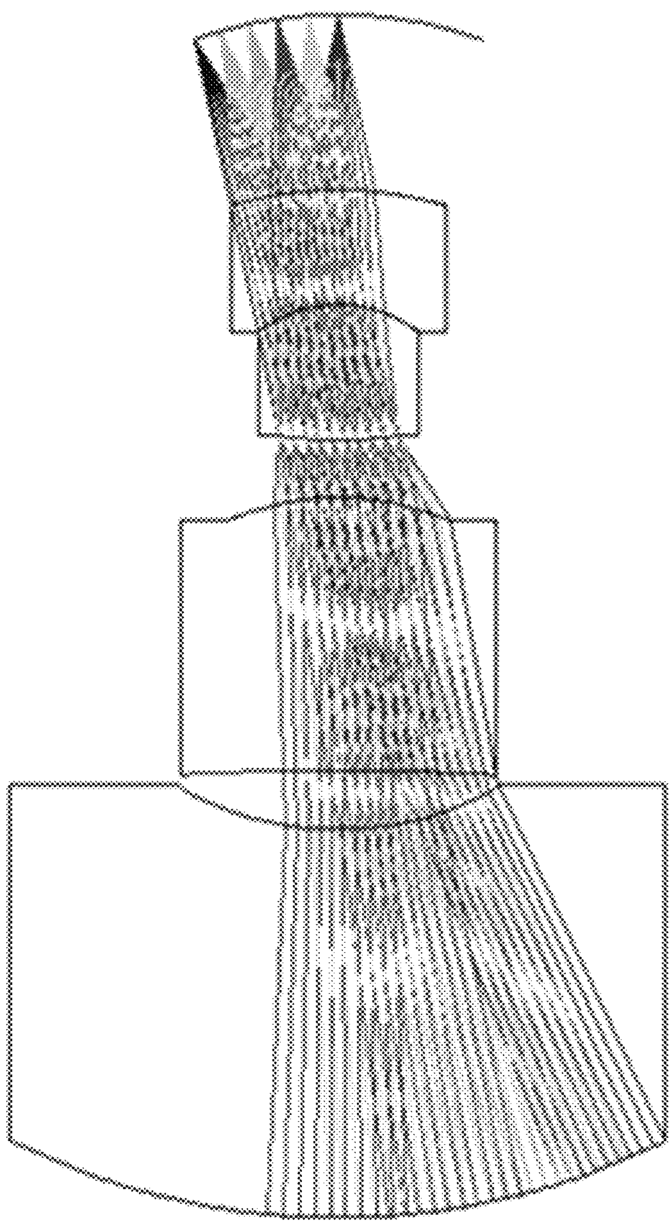


FIG. 11

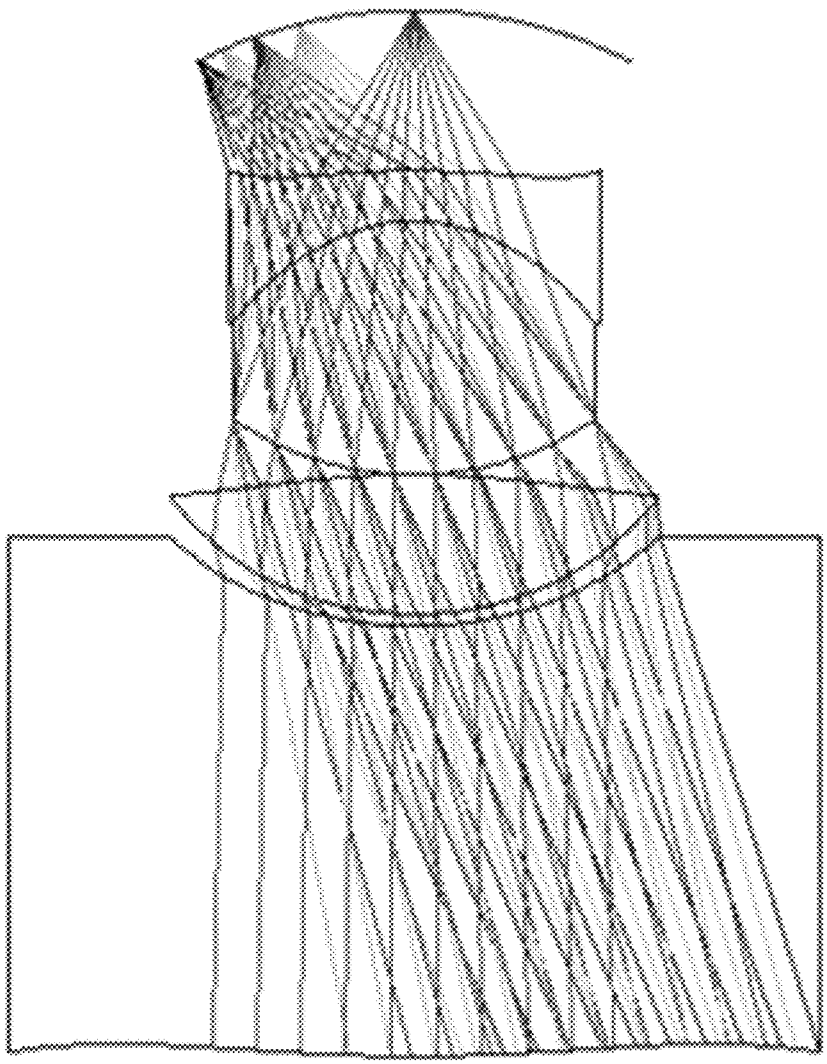


FIG. 12

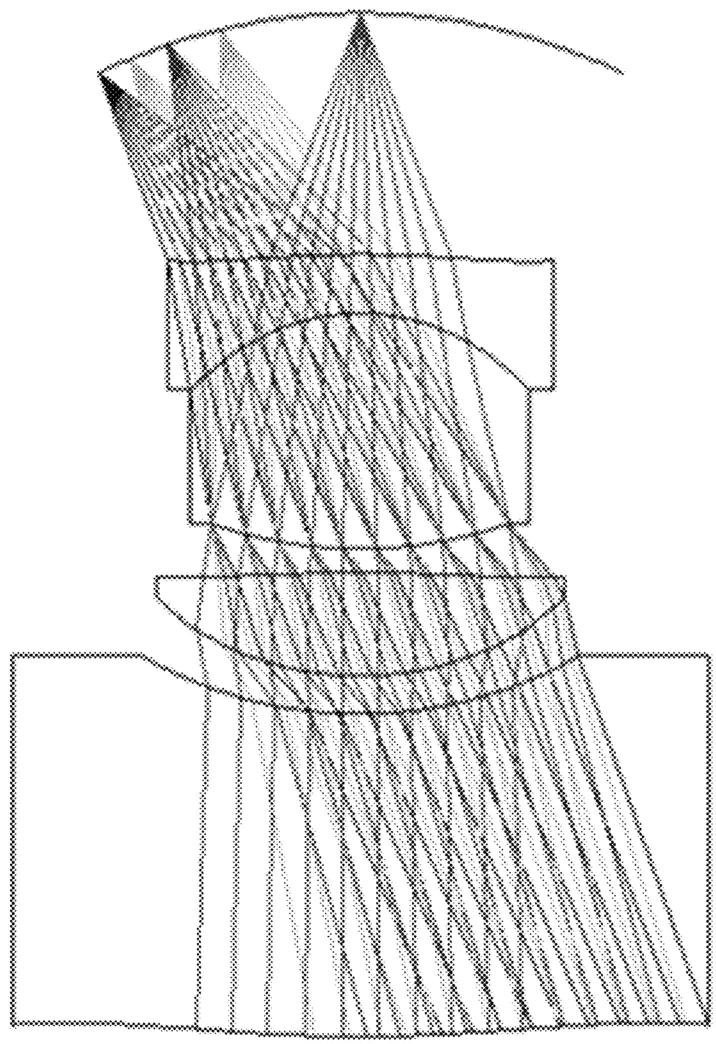


FIG. 13

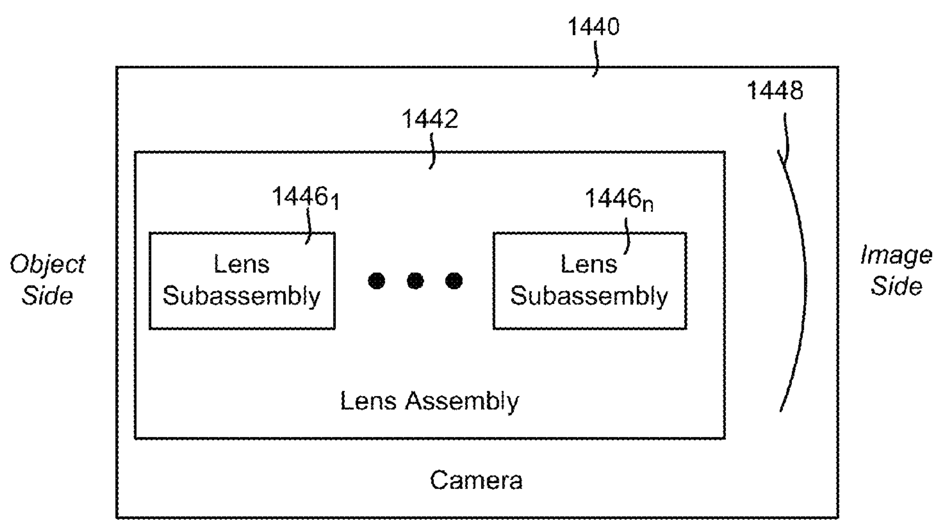

1440
1448
1442
1446$_1$
1446$_n$
Object Side
Lens Subassembly
Lens Subassembly
Image Side
Lens Assembly
Camera

FIG. 14

LENSES FOR CURVED SENSOR SYSTEMS

BACKGROUND

Contemporary lenses are designed/optimized to focus on a planar image surface. However, optical lens systems do not generally have their best focus on a planar imaging surface. For example, spherical lens systems tend to best focus on a roughly hemispherical surface, called the Petzval surface. Much of the complexity of lens design is in forcing the lens system to achieve best focus on a planar imaging surface, far away from the Petzval surface.

Developments in sensor technology have yielded somewhat low resolution curved sensors (with the resolution likely to increase in the future) that provide for improved quality of images. However, with such curved sensors, lenses optimized for planar image surfaces are inappropriate.

SUMMARY

This Summary is provided to introduce a selection of representative concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used in any way that would limit the scope of the claimed subject matter.

Briefly, one or more of various aspects of the subject matter described herein are directed towards multi-element lens assemblies. One example implementation comprises a refractive object-side element having a positive object-facing surface, and one or more lenses optically coupled to the object-side element and configured to focus light onto a curved surface. Another example implementation comprises an object-side subassembly having overall positive refraction, and an image-side subassembly optically coupled to the object-side subassembly. The image-side subassembly is configured to receive light from the object-side subassembly and focus the received light onto a curved surface.

Other advantages may become apparent from the following detailed description when taken in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example and not limited in the accompanying figures in which like reference numerals indicate similar elements and in which:

FIGS. **1-3** are representations of example two-element lens assemblies, each including an object-side positive meniscus lens and an image-side biconvex lens, according to one or more example implementations.

FIGS. **4-6** are representations of example three-element lens assemblies, each including an object-side meniscus lens and an image-side subassembly comprising a biconvex lens and negative meniscus lens, according to one or more example implementations.

FIGS. **7-13** are representations of example four-element lens assemblies, each including an object-side positive refractive lens and an image-side negative refractive lens, according to one or more example implementations.

FIG. **14** is block diagram exemplifying a multiple lens assembly incorporated into a camera having a curved sensing surface, according to one or more example implementations

DETAILED DESCRIPTION

Various aspects of the technology described herein are generally directed towards multiple lens (multi-lens) assemblies configured to focus on a curved surface, such as a hemispherical or substantially hemispherical surface, e.g., a curved sensor. Two, three and four element multi-lens assemblies are exemplified herein, however it is understood that multi-lens assemblies having more than four elements, up to any practical number, are feasible. Further, wherever two or more lenses as shown as physically coupled, it is feasible to have a single lens ground, molded or otherwise manufactured as a single element provided that the materials were the same.

It should be understood that any of the examples herein are non-limiting. For instance, any of the refractive optical elements shown herein may be made of any suitable material, e.g., glass or plastic, and such materials may be used alone or in any combination in any lens assembly. Further, one or more reflective elements may be present instead of or in addition to refractive optical elements. As such, the present invention is not limited to any particular embodiments, aspects, concepts, structures, functionalities or examples described herein. Rather, any of the embodiments, aspects, concepts, structures, functionalities or examples described herein are non-limiting, and the present invention may be used various ways that provide benefits and advantages in lens technology in general.

FIG. **1** shows an example two-element refractive optical element assembly **100** including a refractive optical element (e.g., a generally positive meniscus lens **102**) having a positive refractive power from the object-to image direction via a convex-object side surface and concave opposite side. As generally represented in FIG. **1**, the convex object-facing side of the lens **102** has a larger radius of curvature than the opposite image-facing concave side. Note that FIG. **1** is not intended to convey any actual sizes or dimensions.

The positive meniscus lens **102** is coupled to a generally biconvex lens **104** to focus light onto a curved surface **108**. As can be seen in FIG. **1**, the lens **104** is configured to receive light from the lens **102**. The lens **104** has an object-facing side with a smaller radius of curvature than its image/curved surface-facing side.

The lenses **102** and **104** are shown as physically coupled, however it is understood that they may be separated by a suitable gap filled with any liquid or gas, including air. The lenses **102** and **104** may be made of plastic, glass, or one plastic, one glass, for example. The following show data of one example implementation corresponding to FIG. **1**:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
STO	EVENASPH	2.149059	1.143113	1.477866	0.3033693
2	EVENASPH	0.5794461	1.250096	2.454417	−0.8047933
3	EVENASPH	−2.715948	2.577189	2.676481	−0.7515823
IMA	STANDARD	−4.180481	4.085812	−0.4251225	IMA

Surface STO EVENASPH	
Coefficient on r^2	−0.098497123
Coefficient on r^4	−0.040043231
Coefficient on r^6	0.026768729
Coefficient on r^8	−0.061589691
Coefficient on r^10	0.041752082
Coefficient on r^12	0

-continued

Coefficient on r^14	0
Coefficient on r^16	0
Surface 2 EVENASPH	
Coefficient on r^2	−0.45158306
Coefficient on r^4	−0.014772696
Coefficient on r^6	−0.28951155
Coefficient on r^8	0.19693689
Coefficient on r^10	−0.089640559
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 3 EVENASPH	
Coefficient on r^2	−0.03789558
Coefficient on r^4	−0.0063094918
Coefficient on r^6	0.0026530481
Coefficient on r^8	−0.0048491677
Coefficient on r^10	0.0027909406
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **2** is similar to FIG. **1**, and thus shows a two-element assembly **200** having a positive meniscus lens **222** is coupled to a generally biconvex lens **224** to focus light onto a curved surface **228**. Differences between FIG. **1** and FIG. **2** include the thicknesses of the lenses **222** and **224**, as well as the ratio of each assembly's elements' thicknesses.

The following show data of one example implementation corresponding to FIG. **2**:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
STO	EVENASPH	6.432122	1.799185	1.79147	0
2	EVENASPH	4.164469	1.833238	2.654085	0.
3	EVENASPH	−5.779919	2.572927	3.290749	0
IMA	STANDARD	−4.979109	4.4	−0.1449482	IMA

Surface STO EVENASPH	
Coefficient on r^2	0.016949412
Coefficient on r^4	−0.0060254369
Coefficient on r^6	0.002018416
Coefficient on r^8	−0.003288917
Coefficient on r^10	0.0013935683
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 2 EVENASPH	
Coefficient on r^2	0.10488576
Coefficient on r^4	0.0080114777
Coefficient on r^6	−0.013581529
Coefficient on r^8	0.0040498405
Coefficient on r^10	−0.00072005712
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 3 EVENASPH	
Coefficient on r^2	−0.064406122
Coefficient on r^4	−0.0011588418
Coefficient on r^6	−0.00049122944
Coefficient on r^8	0.00020124711
Coefficient on r^10	2.7372079e−005
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **3** is similar to FIGS. **1** and **2**, having a two-element assembly **300** with a positive (object-side) meniscus lens **332** is coupled to a generally biconvex lens **334** to focus light onto a curved surface **338**. The following show data of one example implementation corresponding to FIG. **3**:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STAN-DARD	Infinity	Infinity	0	0
STO	EVENASPH	1.91288	1.110882	1.623566	−0.1702735
2	EVENASPH	0.4475397	1.378157	2.557306	−0.8949009
3	EVENASPH	−2.76981	2.49896	2.797017	−0.7235262
IMA	STAN-DARD	−4.156886	4	−0.4313463	IMA

Surface STO EVENASPH	
Coefficient on r^2	−0.11783356
Coefficient on r^4	−0.03550621
Coefficient on r^6	0.02213866
Coefficient on r^8	−0.043313454
Coefficient on r^10	0.024704316
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 2 EVENASPH	
Coefficient on r^2	−0.7091958
Coefficient on r^4	0.0034960593
Coefficient on r^6	−0.31902203
Coefficient on r^8	0.1978099
Coefficient on r^10	−0.078643857
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 3 EVENASPH	
Coefficient on r^2	−0.035138687
Coefficient on r^4	−0.0051648925
Coefficient on r^6	0.0030843072
Coefficient on r^8	−0.0044482251
Coefficient on r^10	0.002190287
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

In the two-element design, in general there is a high negative conic constant, and hence large relative asphericity. Correction of coma and astigmatism may be done as with the three-element design as described below, and is generally based upon the surfaces remote from the stop and solving simultaneously for zero S_{II} and S_{III}:

$$0=S_{II}+\epsilon_2\cdot S^*_{I2}+\epsilon_3\cdot S^*_{I3}$$

$$0=S_{III}+\epsilon_2^2\cdot S^*_{I2}+\epsilon_3^2\cdot S^*_{I3}$$

where S_{II} and S_{III} are the coma and astigmatism terms of the whole system before correction, respectively, ϵ_2 and ϵ_3 are the ratio of the principal and marginal ray heights at the second and third surfaces and S_{I2}* and S_{I3}* are the additional spherical aberration terms at the second and third surfaces.

Given the relative size of the Δn at those boundaries for optical materials used in the visible, it is apparent that the actual asphericity in terms of surface sag needs to be larger at surface two than at surface three.

FIG. **4** shows a three-element assembly **440** having an object-side positive, generally meniscus lens **442** optically coupled to a generally biconvex intermediate lens **444**. In turn, the intermediate lens **444** is coupled (e.g., physically or at least optically) to a generally negative meniscus lens-shaped lens **446**, which focuses light onto the curved surface **448**.

Although as in FIGS. **1-3**, no sizes or dimensions are intended to be conveyed in FIG. **4**, although the relative radii of curvature of the individual elements and the gaps are such that the focal lengths are appropriate. The following show data of one example implementation corresponding to FIG. **4**:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
STO	EVENASPH	6.644491	0.9350005	4.586162	2.190639
2	EVENASPH	8.539573	1.159836	4.023222	10.7804
3	EVENASPH	4.935623	1.153228	2.607965	−4.112604
4	EVENASPH	−3.927883	0.9223948	2.604223	−0.2457859
5	EVENASPH	−4.481268	2.140144	3.366548	−3.722884
IMA	STANDARD	−4.128595	4.4	0.113461	IMA

Surface 1 EVENASPH	
Coefficient on r^2	0.067316768
Coefficient on r^4	0.0013146276
Coefficient on r^6	0.00035928207
Coefficient on r^8	−1.936854e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 2 EVENASPH	
Coefficient on r^2	0.0017789485
Coefficient on r^4	0.0013930933
Coefficient on r^6	3.0658734e−005
Coefficient on r^8	−9.2314671e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface STO EVENASPH	
Coefficient on r^2	0.042529249
Coefficient on r^4	0.00303047
Coefficient on r^6	0.0044255189
Coefficient on r^8	−0.00060161924
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 4 EVENASPH	
Coefficient on r^2	−0.36101226
Coefficient on r^4	−0.025921905
Coefficient on r^6	−0.0023854566
Coefficient on r^8	0.0022634492
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 5 EVENASPH	
Coefficient on r^2	−0.07956166
Coefficient on r^4	0.0021746083
Coefficient on r^6	6.0171164e−006
Coefficient on r^8	0.00059107681
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **5** shows an embodiment of another three-element assembly **550**. The object-side lens **552** is close to plano-convex, but is still somewhat of a generally a positive meniscus lens. The biconvex lens **554** receives light from the object-side lens **552**, and is shown as being physically coupled to a negative meniscus lens **556**, which focuses the light onto the curved surface **558**.

The following show data of one example implementation corresponding to FIG. **5**:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
STO	EVENASPH	10.04376	2.500336	5.938842	−2.612775
2	EVENASPH	12.47944	0.7280293	3.826284	18.71383
3	EVENASPH	5.209887	1.091996	2.482273	−1.745061
4	EVENASPH	−2.867931	1.300414	2.532966	−1.174326
5	EVENASPH	−5.473922	1.711776	3.566488	4.812232
IMA	STANDARD	−4.024843	4.4	0.457535	IMA

Surface 1 EVENASPH	
Coefficient on r^2	0.062615788
Coefficient on r^4	0.00059644135
Coefficient on r^6	9.8295376e−006
Coefficient on r^8	−9.0673164e−006
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 2 EVENASPH	
Coefficient on r^2	−0.012678592
Coefficient on r^4	−0.00047655241
Coefficient on r^6	−0.00079881155
Coefficient on r^8	5.0952505e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface STO EVENASPH	
Coefficient on r^2	0.036716283
Coefficient on r^4	0.00017478943
Coefficient on r^6	0.001604258
Coefficient on r^8	−0.00029375864
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 4 EVENASPH	
Coefficient on r^2	−0.2496809
Coefficient on r^4	−0.04802043
Coefficient on r^6	−0.037620033
Coefficient on r^8	0.023786848
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 5 EVENASPH	
Coefficient on r^2	−0.071578632
Coefficient on r^4	0.0054829717
Coefficient on r^6	0.00016838389
Coefficient on r^8	0.00044381629
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **6** shows an embodiment of another three-element assembly **660**. The object-side lens **662** is a generally positive meniscus lens. A biconvex lens **664** receives light from the object-side lens **662**, and is shown as being physically coupled to a negative meniscus lens **666**, which focuses the light onto the curved surface **668**.

The following show data of one example implementation corresponding to FIG. **6**:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
STO	EVENASPH	2.982782	1.579595	4.635227	0
2	EVENASPH	8.397587	0.6721739	3.783354	0

-continued

3	EVENASPH	3.775295	1.038479	2.383311	0
4	EVENASPH	−1.307395	0.8361284	2.462342	0
5	EVENASPH	−2.109334	1.640701	3.354517	0
IMA	STANDARD	−3.623487	3.992889	0.2323074	IMA

Surface 1 EVENASPH

Coefficient on r^2	0.026790834
Coefficient on r^4	0.001466062
Coefficient on r^6	0.00018799414
Coefficient on r^8	1.1263726e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 2 EVENASPH

Coefficient on r^2	−0.0075103766
Coefficient on r^4	0.0044773476
Coefficient on r^6	−0.00096070056
Coefficient on r^8	8.9569244e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface STO EVENASPH

Coefficient on r^2	−0.0082692559
Coefficient on r^4	−0.0035430794
Coefficient on r^6	−0.0047729108
Coefficient on r^8	0.0037146523
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

-continued

Surface 4 EVENASPH

Coefficient on r^2	0.012763776
Coefficient on r^4	0.021906493
Coefficient on r^6	0.0034661071
Coefficient on r^8	0.010609723
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 5 EVENASPH

Coefficient on r^2	0.046717901
Coefficient on r^4	0.0094163635
Coefficient on r^6	0.0016692686
Coefficient on r^8	−8.2571674e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIGS. **7-13** are examples of four element lens assemblies. As can be seen, each of these example lens assemblies has a lens closet to the curved sensor that is a negative meniscus lens, (although in the examples of FIG. **12** and FIG. **13** the lenses are close to plano-concave). For purposes of brevity, rather than describe the individual lenses in each of the exemplified four-element lens assemblies, the data for each is provided.

The following show data of one example implementation corresponding to FIG. **7**:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
1	EVENASPH	224.3738	18.41708	95.81648	−11.33441
2	EVENASPH	273.4945	42.98881	81.69407	32.00641
3	EVENASPH	−231.447	13.22963	47.1052	−480.5678
STO	EVENASPH	81.19232	7.7093	11.33238	−73.30876
5	EVENASPH	−33.06094	4.035196	12.72217	17.45717
6	EVENASPH	−27.76914	20.93704	17.26029	4.856911
IMA	STANDARD	−29.79523	32	0.2489563	IMA

Surface 1 EVENASPH

Coefficient on r^2	0.0009050068
Coefficient on r^4	−1.2866628e−007
Coefficient on r^6	−2.9977403e−011
Coefficient on r^8	−6.285853e−016
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 2 EVENASPH

Coefficient on r^2	0.0016432507
Coefficient on r^4	−5.968454e−007
Coefficient on r^6	−5.8903375e−011
Coefficient on r^8	−2.4605836e−014
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 3 EVENASPH

Coefficient on r^2	−0.0027362957
Coefficient on r^4	1.7252281e−006
Coefficient on r^6	−1.9753377e−009
Coefficient on r^8	4.4952875e−013
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

-continued

Surface STO EVENASPH	
Coefficient on r^2	0.0061035575
Coefficient on r^4	−1.1573733e−005
Coefficient on r^6	−3.8576759e−007
Coefficient on r^8	3.8540073e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 5 EVENASPH	
Coefficient on r^2	−0.048220655
Coefficient on r^4	−0.00017573318
Coefficient on r^6	−8.9580864e−007
Coefficient on r^8	−2.3634797e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 6 EVENASPH	
Coefficient on r^2	−0.022321611
Coefficient on r^4	−2.5698424e−005
Coefficient on r^6	−1.2705637e−008
Coefficient on r^8	5.0233863e−010
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **8** example lens assembly details:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
1	EVENASPH	162.123	32.50005	119.0927	3.010826
2	EVENASPH	129.3732	34.26242	81.72527	4.196508
3	EVENASPH	32.65833	5.173827	23.27261	−2.239026
4	EVENASPH	51.06849	3.007101	19.19739	−5.892531
STO	EVENASPH	31.85256	5.302895	10.03037	24.96704
6	EVENASPH	−24.50952	4.964779	9.685754	20.14663
7	EVENASPH	−27.137	14.95837	15.27177	−6.28567
IMA	STANDARD	−24.65858	32	0.3400413	IMA

Surface 1 EVENASPH	
Coefficient on r^2	0.00026574669
Coefficient on r^4	1.3090292e−007
Coefficient on r^6	−8.067507e−011
Coefficient on r^8	3.2095808e−015
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 2 EVENASPH	
Coefficient on r^2	0.00084216787
Coefficient on r^4	6.1215846e−007
Coefficient on r^6	−5.3812441e−010
Coefficient on r^8	3.5072263e−014
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 3 EVENASPH	
Coefficient on r^2	0.0092935737
Coefficient on r^4	−5.5951183e−006
Coefficient on r^6	−7.2230948e−008
Coefficient on r^8	−7.3651341e−010
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

-continued

Surface 4 EVENASPH	
Coefficient on r^2	−0.0024420196
Coefficient on r^4	−2.2371721e−006
Coefficient on r^6	−8.2333791e−008
Coefficient on r^8	−4.4480187e−010
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface STO EVENASPH	
Coefficient on r^2	0.0097938162
Coefficient on r^4	−2.3705972e−006
Coefficient on r^6	4.256789e−007
Coefficient on r^8	−1.4665789e−010
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 6 EVENASPH	
Coefficient on r^2	−0.073096589
Coefficient on r^4	5.7190799e−005
Coefficient on r^6	4.6297098e−007
Coefficient on r^8	−1.1106303e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 7 EVENASPH	
Coefficient on r^2	−0.014538394
Coefficient on r^4	4.4184008e−005
Coefficient on r^6	3.8845346e−007
Coefficient on r^8	3.6819816e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **9** example lens assembly details:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
1	EVENASPH	62.96768	44.60342	66.41456	0.3010589
2	EVENASPH	31.11318	0.7130898	27.68156	1.258264
3	EVENASPH	24.76477	14.99275	26.88566	1.960634
4	EVENASPH	115.5418	0.1125	19.6447	107.2977
STO	EVENASPH	38.72699	10.74507	17.99032	10.32326
6	EVENASPH	−17.98552	3.940343	18.76694	2.402588
7	EVENASPH	−26.68607	10.7144	22.89597	2.670887
IMA	STANDARD	−21.95436	21.99506	0.4361121	IMA

Surface 1 EVENASPH

Coefficient on r^2	−0.0027228227
Coefficient on r^4	2.7447576e−007
Coefficient on r^6	−8.0962734e−011
Coefficient on r^8	−1.1754249e−013
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 2 EVENASPH

Coefficient on r^2	−0.00080108496
Coefficient on r^4	1.7707049e−005
Coefficient on r^6	1.2244301e−008
Coefficient on r^8	1.5406142e−010
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 3 EVENASPH

Coefficient on r^2	0.010033911
Coefficient on r^4	9.1856009e−006
Coefficient on r^6	−7.4005883e−009
Coefficient on r^8	−2.3732676e−011
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 4 EVENASPH

Coefficient on r^2	−0.014248381
Coefficient on r^4	2.4639797e−005
Coefficient on r^6	−3.0974358e−007
Coefficient on r^8	2.1326118e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface STO EVENASPH

Coefficient on r^2	0.0031486196
Coefficient on r^4	−6.719473e−006
Coefficient on r^6	−4.2952055e−007
Coefficient on r^8	2.3378143e−010
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 6 EVENASPH

Coefficient on r^2	−0.024585082
Coefficient on r^4	−0.00015759285
Coefficient on r^6	7.5876778e−007
Coefficient on r^8	−1.7075289e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 7 EVENASPH

Coefficient on r^2	−0.012329076
Coefficient on r^4	−1.0162983e−005
Coefficient on r^6	1.9008622e−007
Coefficient on r^8	−5.7975021e−010
Coefficient on r^10	0

-continued

Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **10** example lens assembly details:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
1	EVENASPH	15.48462	6.4366753	18.01328	0.7350255
2	EVENASPH	8.848879	0.55726	11.00158	1.003955
3	EVENASPH	9.032038	6.399996	10.93563	1.201861
4	EVENASPH	52.28122	0.6596292	8.418669	−102.507
STO	EVENASPH	11.75226	4.029279	5.893034	7.760635
6	EVENASPH	−5.062495	1.4752	6.311816	0.8644125
7	EVENASPH	−9.769045	3.78492	7.504619	0.3084521
IMA	STANDARD	−8.85309	8.334322	0.4148249	IMA

Surface 1 EVENASPH	
Coefficient on r^2	−0.0071907745
Coefficient on r^4	3.5659214e−005
Coefficient on r^6	−6.2172173e−008
Coefficient on r^8	−4.0974779e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 2 EVENASPH	
Coefficient on r^2	−0.0088366866
Coefficient on r^4	0.00040564053
Coefficient on r^6	9.3202089e−007
Coefficient on r^8	−1.0213473e−007
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 3 EVENASPH	
Coefficient on r^2	0.017895107
Coefficient on r^4	0.00040857664
Coefficient on r^6	−3.2173946e−006
Coefficient on r^8	−3.0588291e−007
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 4 EVENASPH	
Coefficient on r^2	−0.038343155
Coefficient on r^4	0.00049343981
Coefficient on r^6	−2.6827802e−005
Coefficient on r^8	7.0872313e−007
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface STO EVENASPH	
Coefficient on r^2	0.0057852056
Coefficient on r^4	0.00020538583
Coefficient on r^6	−3.5523241e−005
Coefficient on r^8	−1.8504176e−007
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 6 EVENASPH	
Coefficient on r^2	−0.070725522
Coefficient on r^4	−0.001121991
Coefficient on r^6	5.9885948e−005
Coefficient on r^8	8.3858477e−006
Coefficient on r^10	0
Coefficient on r^12	0

-continued

Coefficient on r^14	0
Coefficient on r^16	0
Surface 7 EVENASPH	
Coefficient on r^2	−0.019022298
Coefficient on r^4	0.00011123481
Coefficient on r^6	2.6657465e−005
Coefficient on r^8	−2.3693164e−007
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **11** example lens assembly details:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
1	EVENASPH	34.46149	21.6879	36.8607	0
2	EVENASPH	22.25803	3.200012	18.05265	0
3	EVENASPH	−43.37931	15.34823	17.64078	0
4	EVENASPH	−15.71166	3.197076	12.67488	0
STO	EVENASPH	33.63017	7.563545	6.623186	0
6	EVENASPH	−9.632602	6.408138	9.044731	0
7	EVENASPH	−25.75564	9.774625	12.14408	0
IMA	STANDARD	−24.33541	16.11549	0	IMA

Surface 1 EVENASPH	
Coefficient on r^2	−0.0023330882
Coefficient on r^4	−2.0063176e−006
Coefficient on r^6	1.712178e−009
Coefficient on r^8	−4.8168342e−012
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 2 EVENASPH	
Coefficient on r^2	0.0039164919
Coefficient on r^4	8.2553246e−006
Coefficient on r^6	2.4164262e−007
Coefficient on r^8	3.8123788e−010
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 3 EVENASPH	
Coefficient on r^2	0.012882344
Coefficient on r^4	−5.6454175e−005
Coefficient on r^6	3.7235058e−007
Coefficient on r^8	−2.5203063e−009
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

-continued

Surface 4 EVENASPH	
Coefficient on r^2	−0.0052614684
Coefficient on r^4	0.0001875086
Coefficient on r^6	−2.2633249e−006
Coefficient on r^8	1.5881566e−008
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface STO EVENASPH	
Coefficient on r^2	0.0034148683
Coefficient on r^4	0.00026669857
Coefficient on r^6	−4.7164879e−006
Coefficient on r^8	8.4829314e−008
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 6 EVENASPH	
Coefficient on r^2	−0.016533876
Coefficient on r^4	−0.00028941833
Coefficient on r^6	−1.0187295e−005
Coefficient on r^8	9.2891838e−007
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 7 EVENASPH	
Coefficient on r^2	−0.0062723283
Coefficient on r^4	4.010936e−005
Coefficient on r^6	6.2071785e−007
Coefficient on r^8	1.0114067e−008
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **12** example lens assembly details:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
1	EVENASPH	7.057435	2.988707	5.674679	1.814324
2	EVENASPH	3.258223	0.08128771	3.426519	−0.5657294
3	EVENASPH	2.901909	0.9694701	3.392434	0.05291388
4	EVENASPH	−31.11675	0	3.368211	0
STO	EVENASPH	2.944861	1.764741	2.528473	−0.3409325
6	EVENASPH	−1.574102	0.3459662	2.519126	−1.902648
7	EVENASPH	−5.186811	1.116115	2.59444	−28.09088
IMA	STANDARD	−3.470872	3.036393	0.2865449	IMA

Surface 1 EVENASPH	
Coefficient on r^2	−0.032551323
Coefficient on r^4	−0.0048517168

-continued

Coefficient on r^6	−0.00019793491
Coefficient on r^8	1.3280715e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 2 EVENASPH	
Coefficient on r^2	0.028308733
Coefficient on r^4	−0.002587907
Coefficient on r^6	0.0076772372
Coefficient on r^8	−0.0013908962
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 3 EVENASPH	
Coefficient on r^2	0.052136909
Coefficient on r^4	−0.0025480509
Coefficient on r^6	0.0063986009
Coefficient on r^8	−0.00051891927
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 4 EVENASPH	
Coefficient on r^2	−0.055267632
Coefficient on r^4	0.0010476998
Coefficient on r^6	0.0031384482
Coefficient on r^8	−0.00032573638
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface STO EVENASPH	
Coefficient on r^2	0.052303764
Coefficient on r^4	0.0013254458
Coefficient on r^6	0.011041063
Coefficient on r^8	−0.0042722676
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 6 EVENASPH	
Coefficient on r^2	−0.12060363
Coefficient on r^4	0.032302384
Coefficient on r^6	−0.032302727
Coefficient on r^8	−0.0035113698
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0
Surface 7 EVENASPH	
Coefficient on r^2	0.015231714
Coefficient on r^4	0.012736379
Coefficient on r^6	0.005512558
Coefficient on r^8	0.0040815702
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **13** example lens assembly details:

Surf	Type	Radius	Thickness	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity	0	0
1	EVENASPH	5.859769	1.839874	3.996322	−0.0417652
2	EVENASPH	2.831865	0.2170869	2.506635	−0.5090163
3	EVENASPH	2.306807	0.5873021	2.334853	0.5058974
4	EVENASPH	80.21697	0.1369206	2.228267	4182.971

-continued

STO	EVENASPH	3.152057	1.341948	1.701928	−1.099714
6	EVENASPH	−1.410627	0.3361722	1.949082	−1.114667
7	EVENASPH	−4.960287	1.375117	2.223864	−21.00731
IMA	STANDARD	−3.508075	3.001053	0	IMA

Surface 1 EVENASPH	
Coefficient on r^2	−0.02899649
Coefficient on r^4	−0.010051793
Coefficient on r^6	−0.00048326198
Coefficient on r^8	9.7659737e−005
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 2 EVENASPH	
Coefficient on r^2	0.024143729
Coefficient on r^4	−0.00055718234
Coefficient on r^6	0.0058160331
Coefficient on r^8	−0.0023649112
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 3 EVENASPH	
Coefficient on r^2	0.049071226
Coefficient on r^4	0.0097786873
Coefficient on r^6	0.0089052798
Coefficient on r^8	0.0023761706
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 4 EVENASPH	
Coefficient on r^2	−0.050967198
Coefficient on r^4	0.0062549297
Coefficient on r^6	0.013279928
Coefficient on r^8	−0.0047169231
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface STO EVENASPH	
Coefficient on r^2	0.036069468
Coefficient on r^4	−0.0019326477
Coefficient on r^6	0.010929391
Coefficient on r^8	−0.019845718
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 6 EVENASPH	
Coefficient on r^2	−0.04959238
Coefficient on r^4	−0.03986785
Coefficient on r^6	−0.040731282
Coefficient on r^8	0.012511117
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

Surface 7 EVENASPH	
Coefficient on r^2	0.022642757
Coefficient on r^4	0.010081191
Coefficient on r^6	0.013106754
Coefficient on r^8	0.00031467056
Coefficient on r^10	0
Coefficient on r^12	0
Coefficient on r^14	0
Coefficient on r^16	0

FIG. **14** shows an example of a camera **1440** containing a lens assembly **1442** constructed in accordance with the technology described herein. As can be seen, lens subassemblies **1446_1**-**1446_n** focus light, which may be visible light and/or other light (such as infrared) onto a curved surface **1448**.

Additional Example Details

In general, some of the exemplified designs are relatively wide-aperture and wide-field and may be constructed using high-order aspheres. Designs may be re-optimized for a lower aperture, and higher-order terms may be dropped. This brings the designs within reach of a description using first-order and third-order wavefront expansions—the domain in which Seidel aberration analysis is appropriate and hence enables the optical function of the various surfaces to be explained.

The lens elements are in general thick in comparison to their separation and therefore a thin-lens solution is not appropriate.

Seidel aberration	Comment	Correction needed
S_I	Spherical aberration	Yes
S_{II}	Coma	Yes
S_{III}	Astigmatism	Yes
S_{IV}	Petzval sum (field curvature if S_{III} = 0)	No
S_V	Distortion	No*
C_I	Longitudinal chromatic aberration	Yes
C_{II}	Transverse chromatic aberration	Yes

In these designs, field curvature is effectively left to float and the image sensor is placed at the Petzval surface. Note that distortion correction is desirable in principle, but the effect of correcting distortion is to flatten the image field and hence negate some of the benefits of the curved image field so it is left uncorrected.

Note that even without the aspheres, the system at moderate apertures is well-corrected for the first three primary monochromatic aberrations. The primary offender is astigmatism, and there are only a few wavelengths of this at f/4; by comparison a thin-lens of similar power at the stop would have about 21 wavelengths of astigmatism. Low starting aberrations tend to be helpful to the design.

In one aspect, the design is pseudo-symmetric, which makes coma and transverse color low by default. The design is also generally pseudo-centro-symmetric, which makes coma and astigmatism low at the external surfaces of the lens (the principal ray is roughly normal to the surface).

One or more implementations start with a positive curvature (as with most lenses), as well as having the first element overall positive to help minimize total track. One or more implementations use one aplanatic surface before the stop and/or in which the marginal ray is close to normal at this surface, and make the surface at the stop nearly concentric with the preceding surface. The curvature may be used to control astigmatism as desired.

The buried surface both corrects for longitudinal color and introduces overcorrected (negative) spherical aberration, which helps compensate for that at the external surfaces of the lens.

If an implementation allows aspheres, astigmatism maybe corrected by introducing an asphere into a surface remote from the stop. The effect of the asphere is to introduce a spherical aberration term that, dependent on the ratio of the principal ray height to the marginal ray height will correct some or all of the astigmatism. However, there is likely some coma. Because this was already low, this additional coma is corrected in another surface.

Correcting the residual spherical aberration can be done by an asphere at the stop. One basic approach finds a Gaussian solution that gives low lateral and longitudinal color, ignoring field curvature but using some of the resulting freedom to minimize total track, which is helpful if a solution has low coma and spherical aberration overall so that aspherics do not have to be excessive. Astigmatism may be corrected using a back surface (or the surface furthest from the stop). Coma may be corrected using a front surface (or the surface next furthest from the stop). Remaining spherical aberration may be corrected using the surface at the stop

CONCLUSION

While the invention is susceptible to various modifications and alternative constructions, certain illustrated embodiments thereof are shown in the drawings and have been described above in detail. It should be understood, however, that there is no intention to limit the invention to the specific forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions, and equivalents falling within the spirit and scope of the invention.

What is claimed is:

1. A system comprising:

a curved surface; and

a two element lens assembly, the two element lens assembly comprising:

a first aspherical refractive element with positive refractive power having a first object-facing surface and a first image-facing surface;

a second aspherical refractive element comprising a second object-facing surface and a second image-facing surface, the second object-facing surface coupled to the first image-facing surface of the first aspherical refractive element, the second aspherical refractive element configured to focus light onto the curved surface, the second aspherical refractive element comprising a biconvex lens; and

an aspherical buried surface defined by the interface of the second object-facing surface of the second aspherical refractive element and the first image-facing surface of the first aspherical refractive element, the aspherical buried surface configured to introduce negative spherical aberration.

2. The system of claim **1**, wherein the first aspherical refractive element comprises a positive meniscus lens.

3. The system of claim **1**, wherein the first object-facing surface has a radius of curvature that is greater than a radius of curvature of the first image-facing surface.

4. The system of claim **1**, wherein the biconvex lens is physically coupled to the first aspherical refractive element.

5. The system of claim **1**, wherein the second object-facing surface has a radius of curvature that is less than a radius of curvature of the second image-facing surface.

6. The system of claim **1**, wherein the curved surface comprises a curved sensor.

7. The system of claim **1**, wherein the curved surface comprises a hemispherical surface.

8. A lens assembly comprising:

an object-side subassembly having overall positive refraction; and

an image-side subassembly optically coupled to the object-side subassembly, the image-side subassembly configured to receive light from the object-side subassembly and focus the received light onto a curved surface, the image-side subassembly comprising:

a first aspherical refractive element having a first object-facing surface and a first image-facing surface;

a second aspherical refractive element comprising a second object-facing surface and a second image-facing surface, the second object-facing surface coupled to the first image-facing surface of the first aspherical refractive element; and

an aspherical buried surface defined by the interface of the second object-facing surface of the second aspherical refractive element and the first image-facing surface of the first aspherical refractive element, the aspherical buried surface configured to introduce negative spherical aberration.

9. The lens assembly of claim **8**, wherein the object-side subassembly comprises a positive meniscus lens.

10. The lens assembly of claim **8**, wherein the image-side subassembly comprises a biconvex lens and a negative meniscus lens.

11. The lens assembly of claim **10**, wherein the object-side subassembly comprises at least two refractive optical elements.

12. The lens assembly of claim **8**, having an object-side positive refractive lens, at least two intermediary lenses, and an image side negative refractive lens.

13. The lens assembly of claim **8**, wherein the second aspherical refractive element comprises a single biconvex lens.

14. A camera comprising:

a curved surface; and

a lens assembly configured to focus light onto the curved surface, the lens assembly comprising:

a first lens assembly;

a second lens assembly optically coupled to the first lens assembly, the second lens assembly configured to receive light from the first lens assembly and focus the received light onto the curved surface, wherein the second lens assembly comprises a biconvex lens, the second lens assembly comprising an aspherical buried surface defined by the interface of a first and second lens, the aspherical buried surface configured to introduce negative spherical aberration.

15. The camera of claim **14**, wherein the first lens assembly comprises an aspherical object-side positive refractive lens and the second lens assembly comprises an aspherical image side negative refractive lens.

16. The camera of claim **14**, wherein the biconvex lens of the second lens assembly comprises an object-facing side having a radius of curvature that is less than a radius of curvature of a negative image-facing side.

17. The camera of claim **14**, wherein the first lens assembly comprises a positive meniscus lens.

18. The camera of claim **14**, wherein the second lens assembly is a two element lens assembly, comprising two optically coupled elements.

19. The camera of claim **14**, wherein the biconvex lens of the second lens assembly receives light from the first lens assembly, the biconvex lens optically coupled to a negative meniscus lens focuses the light onto the curved surface.

20. The camera of claim **19**, wherein the biconvex lens is physically coupled to the negative meniscus lens.

* * * * *